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DISCUSSION OF A KINETIC THEORY OF GRAVITATION, II; AND SOME NEW EXPERIMENTS IN GRAVITATION.

Second Paper.

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A year ago I had the honor to present to this Society the first paper under the present title. The second, or experimental part of that paper, appeared to show that equal masses of zinc and bismuth, also of iron, and presumably of other metals and substances, do not have exactly equal weights; in other words, that the *mass-weight* relationship differs in different substances. For instance, a given mass of bismuth appears to weigh a little more than an equal mass of zinc; or, to state it differently, as in the pendulum experiments following, gravity acts more strongly per unit of mass on bismuth than on zinc.

When established, this is a fundamental fact of supreme importance; and the present paper is devoted wholly toward its confirmation, leaving theoretical consideration for future papers.

As the following experiments relate only to the *mass-weight* difference between zinc and bismuth, I shall, for simplicity, refer to it as the "zinc-bismuth effect."

Of the several experiments detailed in the first paper, that of the two gravity pendulums is the simplest and most easily understood, the most accurate and reliable, and has brought out most suggestions of possible sources of error. The latter are all considered in the following review and extension of the pendulum experiments; and the conditions as to length of rods, and weight and shape of bobs, have been widely varied. In *every* case the former zinc-bismuth effect has been confirmed, and in *no* instance has there been any negative or equivocal result.

PROC. AMER. PHIL. SOC., VOL. LXI, M, NOV. 16, 1922.

Review and Extension of Gravity Pendulum Experiments Described in First Paper.

Most of this work has been purposely delayed until after publication of the first paper,[1] in the hope that if any source of large error had been overlooked at the time of writing that paper, it would be pointed out by some one. Nothing of this sort has been brought to my attention.

The next four or five pages, as far as Table I., are in substance quoted from the first paper.

Plate I. shows the pendulum apparatus as originally installed, together with driving clocks at the top, added later for long-continued observations.

A starting cradle, moving in guides on the low table just below the cylindrical zinc and bismuth bobs, serves to start the pendulums swinging exactly together in any desired amplitude. After pushing the bobs sufficiently to the left, the cradle is suddenly withdrawn to the right, leaving the bobs free. This device is entirely satisfactory in performance.

A horizontal thick plate of hardened steel is very firmly bolted to the lower flange of a heavy iron I beam imbedded in the masonry of the ceiling and walls of the room. The plate is dropped 6.5 cm. below the beam by cylindrical iron spacers through which the bolts pass, and is carefully leveled. Near one edge of the upper face of the plate is a long shallow \/ groove of 90° angle, with a slightly rounded bottom carefully ground straight and polished after the plate was hardened.

From this plate hang two exactly similar pendulums of about 2.284 m. effective length and 15.2 cm. apart. Each pendulum rod, except for a few centimeters at each end, is of mild steel, perfectly straight, and 1.6 mm. diam. Both rods were cut from the same specimen, so as to have the same temperature coefficient. The upper 20 cm. of each rod is 0.4 cm. diam. round steel with fine screw thread and thumb nut on its upper part. The thumb nut has eight radial holes for a long brass pin, the whole adapted to effect very fine adjustment of pendulum length. The thumb nut rests on the horizontal face of a 60° triangular "knife-edge" of hardened steel

[1] Proc. Am. Phil. Soc., Vol. LX., No. 2, 1921.

through which the rod passes. The upper part of the rod is slightly flattened on one side by grinding, and a thumb screw in one end of the knife-edge block bears against the flattened side of the rod and clamps it firmly in the block after each length adjustment is made. The knife-edge, ground true and sharp, rests in the plate groove above described, while the rod passes downward through an opening in the side of the plate.

Each pendulum rod terminates at its lower end in a straight brass rod 13 cm. long and 0.4 cm. diam. A perfectly straight horizontal steel pin passes loosely through the brass rod near its lower end, and on this pin the cylindrical bob, or weight as I shall hereafter call it, rests.

Fig. 1 shows the upper and lower parts of one pendulum in detail, with the bismuth weight in place.

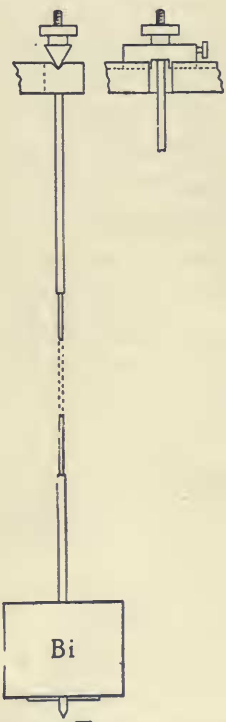

FIG. 1.

The brass rod at the lower end passes just freely through the weight, and accurately in its axis. A weight is easily removed from either pendulum by lowering it after the pin is withdrawn, and another weight may be substituted by reversing the procedure. While this is being done the pendulum rod is kept taut by another temporary, radially slotted, lead weight applied just above, and resting on the upper end of the brass rod. Thus the weights forming the bobs of the two pendulums may readily be exchanged without disturbing anything else.

The weights to be compared, bismuth and zinc in the first instance, were made very accurately the same in height, and with upper and lower ends as nearly plane and parallel as possible, by careful grinding on a perfectly flat surface.

It is essential that the centers of gravity of the weights be exactly the same distance above their supporting pins. To assure this, each weight was adjusted to have its center of gravity exactly midway between its upper and lower ends by the following procedure: The pendulums having been started swinging with a definite amplitude and brought to synchronism by length adjustment, one of the weights was turned over; this at first resulted in loss of synchronism at the same amplitude. Then, as indicated, the upper or lower cylindrical portion was slightly reduced in diameter by turning off or sandpapering in the lathe. Again the pendulums were synchronized, and again the same weight was turned over and synchronism tested. This process was repeated again and again with each weight until either could be turned over without affecting synchronism in the slightest observable degree. In making these adjustments very minute departure from synchronism could be detected in half an hour at the turning points of the swing.

Instead of making the cylinders the same in diameter, they were made approximately the same in *weight,* about 1.377 kg., so that when they were exchanged the length of the pendulum rods would not be affected. Otherwise it would have been necessary to apply corrections for the elastic modulus of the rods and for their effect on the *center of oscillation of the weights* with every exchange. The latter correction would have been very large, and liable to error.

Finally, the zinc and bismuth pendulums were adjusted to synchronism as perfectly as possible in 40-minute runs with initial amplitude of 35 cm. As it turned out, the bismuth pendulum was then materially *longer* than the zinc one. It was the whole aim of the pendulum experiments to detect and measure this difference if it existed.

Next, the weights were exchanged, so that in effect the bismuth pendulum was now the *shorter* one by *double* the former difference. On again starting the pendulums, at the former amplitude, loss of synchronism was easily observable in 2 minutes—the bismuth gaining. In half an hour the bismuth gain was very large. In the same and other forms this experiment was repeated many times, and *always* with the same unequivocal result.

Equality of air resistance was effected by attaching small paper vanes to opposite sides of the bismuth normal to the line of swing, of such size as to produce air damping equal to that of the zinc as shown by equal time loss of amplitude. The necessary vanes are very small.

It appears from this experiment that the earth's gravitation field, which is here the accelerating force, grips the bismuth more strongly per unit of mass than it grips the zinc per unit of mass; in other words, a given mass of bismuth appears to *weigh more* than the same mass of zinc. Apparently the length of a standard seconds pendulum may depend on the material of which it is made.

The greater diameter of the zinc cylinder slightly lowers its center of oscillation; and this accounts for about 10 per cent. of the effect above described, as determined by elaborate experimentation which need not be detailed here, and which was approximately verified by computation.

A pair of high-grade, weight-driven clock movements were next added to the apparatus, as shown in the upper part of Plate VII., and adapted to drive the pendulums continuously at an amplitude of 13 cm.

After synchronizing the zinc and bismuth pendulums at this amplitude, the zinc and bismuth weights were exchanged as heretofore described. Then they were started exactly together and allowed to run until they were again exactly together, the bismuth having thus gained two full beats. Half the elapsed time was taken as the value of *one* beat gain.

Again the pendulums were synchronized, the zinc weight now being on the pendulum formerly occupied by the bismuth weight; then the weights were exchanged as before, the pendulums started together, and allowed to run until the bismuth had gained two beats as formerly. This procedure was for the purpose of verifying the first finding and to expose any considerable difference there might be in the performance of the driving clocks. No such difference was found; yet for verification the same procedure was followed in the next experiments.

A cylinder of very pure iron was next prepared, of exactly the same height, and approximately the same weight as the zinc and bismuth cylinders, and adjusted for center of gravity with the same care.

The iron weight or cylinder was then compared with the zinc weight and with the bismuth weight, with the same care used in comparing the zinc and bismuth as above described. The iron gave results intermediate between those of zinc and bismuth.

Table I. shows the performance of the zinc-iron, the iron-bismuth, and the zinc-bismuth combinations. The measurements of time required to gain one beat check and confirm each other remarkably well.

As the pendulums make about 2,388 oscillations per hour, the bismuth gains one beat, or oscillation, in about 17.432; but as before pointed out, the real zinc-bismuth effect is only half of this, say, one

TABLE I.

Zinc-Iron	15½ hrs. 18½ "	Mean 17 hrs.
Iron-Bismuth	13 hrs. 12½ " 13½ "	Mean 13 hrs.
Zinc-Bismuth	7 hrs. 20 min. 7 " 16 "	Mean 7.3 hrs.

Zinc — Iron — Bismuth

Zinc–Iron: 17 hrs. Iron–Bismuth: 13 hrs.

Zinc–Bismuth: 7.3 hrs.

Reciprocals:

$$\frac{1}{17} + \frac{1}{13} = \frac{1}{7.36}$$

part in 35,000. Thus a *weight-mass difference* effect appears fairly well established and is impressive.

Effect of Unequal Weight of Bobs.—In the foregoing experiments the zinc cylinder or bob weighed about 7 grams *less* than the bismuth (about ½ per cent.); and it was known that this would tend to "speed up" the zinc and make the period difference or "zinc-bismuth effect" appear *less* than if the bobs were equal in weight. But it was thought that the effect of this weight difference was so small that it would not be worth while to delay the experiments several days to correct it, though computation would have shown differently.

Last summer a review and extension of the pendulum experiments was commenced, and the first thing done was correction of the weight deficiency of the zinc cylinder. This was effected by placing a tightly fitting equatorial band of thin sheet zinc on the cylinder and driving it slightly one way or the other until perfect adjustment of center of gravity was had, as and for the reason heretofore explained. Finally, the zinc band was secured from accidental displacement by several very small drops of solder at its edges. As it turned out, the banded zinc, instead of being 7 grams lighter than the bismuth as before correction, was then about one tenth gram heavier than the bismuth. This latter difference is trivial and was not corrected.

The effect of equalizing the weight of the zinc and bismuth was unexpectedly large. Instead of the bismuth gaining one beat in 7 hours 18 minutes, as shown in Table I., it now gained a beat in 5 hours 11 minutes.

The reason for the large disturbing effect of any considerable weight difference between the bobs is perfectly clear. It is due to the distribution of weight in the equal pendulum rods. Obviously, if we could have stretchless and weightless rods, even large weight differences between the bobs, whatever they were made of, would have no disturbing effects except those due to different diameters, which would change their center of oscillation and air resistance.

But the center of oscillation of a pendulum rod alone is *very far* above that of its bob, and it is the resultant center of oscillation of the combined rod and bob that we have to deal with. Clearly, then, if we reduce the weight of a bob, we raise the center of oscillation of the combination and thus shorten its period.

The new and enlarged value of the zinc-bismuth effect found, as above described, clearly does not invalidate the usefulness of Table I. as a check on the accuracy of the work done before correcting the weight of the zinc bob. If the new value were introduced in a similar table, it would simply increase the zinc-iron effect (less hours for one beat gain of iron) as well as the zinc-bismuth effect, and show that the iron is more closely related to bismuth than to zinc in effect producing qualities.

Inequality of bob weights is much the largest and most dangerous source of error I have found in the pendulum experiments; dangerous because it is not very obvious (no one has pointed it out), and if overlooked may lead to wholly erroneous results—even reversing the sign of the zinc-bismuth effect. I have said so much about it for the guidance of others who may wish to try pendulum experiments for themselves.

The next step was to make a new pair of zinc and bismuth bobs as nearly as possible exactly like the original pair, except that the zinc cylinder is slightly larger in diameter so as to have the required weight without banding, and the bismuth cylinder purposely has a coarser crystalline structure.

The new castings were made like the old ones, in molds consisting of vertical iron cylinders somewhat larger in diameter than the finished bobs, with an asbestos paper tube extending above. Thus the castings were chilled at their lower end, and rather rapidly cooled throughout.

But before machining, the bismuth casting only, was packed in molding sand in an iron box and gradually heated in a large electric muffle furnace above the melting point of bismuth, and then allowed to cool *very* slowly through the freezing stage of the metal by suitably reducing the heating current in the furnace. This procedure surely resulted in a crystalline structure of very large grains.

Finally, the new cylinders were worked to weight, *length,* parallelism of ends, and adjustment of center of gravity with all the care and patience exercised with the earlier cylinders. The weights of the new and old cylinders are now as follows:

Weight of old zinc	1,383.899	grams
Weight of new zinc	1,383.893	"
Weight of old bismuth	1,383.795	"
Weight of new bismuth	1,383.798	"

Large weighings like these are made with a 2-kilogram Becker balance of the most improved type, easily sensitive to a tenth milligram with full load.

The members of each pair of cylinders are made so closely alike in weight because they are to be superposed on the pendulum rods; and any difference in weight would shift the center of gravity of the pair.

The purpose of the second pair of bobs is, first, to permit comparison of bobs of the same metal—I am often asked to do this; and, second, by superposing the zinc or the bismuth, to provide bobs of double the former weight and very different in shape. It was not expected, however, that even such large variation of weight and shape of bobs would throw any new light on the subject; and it did not, as will appear. This will be gratifying to such of my friends as have been bothered with doubts in these respects.

Next, the old and new bismuth bobs were mounted on the two pendulum rods; synchronized, exchanged, and period difference measured; again synchronized, exchanged, and period difference measured, all as formerly done with *zinc* and bismuth bobs. In addition to this, each bob, after exchanging, was turned over and tested again so as to average out any small errors that might have been left when center of gravity adjustments were made. In these experiments the small paper vanes on the old bismuth cylinder were eliminated in effect by turning them into the line of swing.

In *every* instance the new bismuth *gained* over the old bismuth, but not much. Averaging all the measurements, the mean gain was about .6 mm. per hour measured in middle of swing with a reading telescope. Whole amplitude was about 11.4 cm. Hence somewhere about 190 hours would have been required for a full beat gain, such as takes place in about 5 hours when zinc and bismuth are compared. Therefore, we may call the new bismuth-bismuth effect about 2½ per cent. as large as the normal zinc-bismuth effect.

The above shows too much difference in behavior between old and new bismuth cylinders to be attributed to experimental errors. It seems not unlikely, then, that there is a real *mass-weight* difference between the old and new bismuth cylinders. It is believed that this difference is due to difference in crystalline structure. If this is the true explanation, it is exceedingly interesting in showing that physical condition affects the relation of weight and mass in bismuth, and presumably in other substances. Certain other experiments on very different lines, which will be detailed in a future paper, appear to support this view.

But the old and new *zinc* cylinders, when compared with similar care, also showed a similar, though smaller, difference in behavior, the new zinc being faster than the old. This may be due to the fact that the new bob was made of electrolytic zinc, presumably almost chemically pure, while the old one was made of ordinary commercial zinc, presumably not nearly so pure.

The latter and subsequent experiments were greatly facilitated by using a reading telescope located in the plane of the pendulum wires when at rest, and focussed sharply on the nearer wire just above the brass rod which carries the bob. This leaves the farther wire hazy in outline, so that the two wires are easily distinguished as they cross the field of view. When the pendulums are in synchronism, the wires are superposed as they cross the center of the field. In this way very small departures from synchronism can be detected in a few minutes, which would require many times longer to grow sufficiently to be seen with the unaided eye.

Next, both zinc cylinders were mounted on one pendulum rod, the new one above; and both bismuth cylinders on the other rod, the new one above, all as shown in Plate VIII. (the plate, however, showing much shorter pendulum rods). The old bismuth cylinder had its small paper vanes turned normal to line of swing, while the new bismuth cylinder carried a very thin aluminum vane normal to swing, of computed area sufficient to make its air resistance equal that of the new zinc cylinder.

Here we have bobs of double the former weight, and very different in shape. Of course, the periods are slightly shortened.

Then these double bobs were fully compared in the same manner as were the former single bobs. The closely same results are shown in Table II.

Both pendulum rods were next shortened nearly a meter, and a suitably higher table was placed below them, as shown in Plate VIII.

TABLE II.

	Time in Minutes Required for Bi to Gain One Beat.			Single Swings for Bi to Gain One Beat.	Double Zn-Bi Effect Observed $\times 10^{-6}$.	Zn-Bi Effect Observed $\times 10^{-6}$.	Radius of Gyration Effect Computed $\times 10^{-6}$.	Zn-Bi Effect Corrected $\times 10^{-6}$
	Synchronized.		Mean.					
	Bi North.	Bi South.						
Long Pendulums.								
Single Bobs								
Zn 7 gms. deficient in wt.	436	440	438	17,450	57.3	28.6	9.0	19.6 = 1/51,000
Zn and Bi wts. equal	314	308	311	12,390	80.7	40.3	9.0	31.3 = 1/32,000
New Zn, New Bi.	301.5	314.5	308	12,270	81.5	40.7	9.0	31.7 = 1/31,600
Double Bobs	298.7	306.8	303	12,110	82.6	41.3	9.2	32.1 = 1/31,200
Short Pendulums.								
Single Bobs, New Zn and Bi	221.2	214	217.6	11,220	89.1	44.6	25.2	19.4 = 1/52,000
Double Bobs	179	193.2	186.1	9,630	103.8	51.9	26.0	25.9 = 1/38,600

PERIODS.

Single Beats per minute.

Long Pendulums, Single Bobs 39.834
" " Double Bobs 39.993
Short Pendulums, Single Bobs 51.546
" " Double Bobs 51.752

The single and double bobs on the shorter rods were compared as before, with results shown in lower part of Table II. But reversal of the larger and smaller time quantities in columns 1 and 2 lead to strong suspicion of experimental errors, probably due to insufficient care in exchanging the bobs after synchronizing. Unfortunately, as the last experiments were made quite recently, there has not been time to repeat them.

Effect of Greater Diameter of Zinc Bobs on Center of Gyration.—In last year's paper this effect, with the long pendulums, was estimated to account for about 10 per cent. of the whole zinc-bismuth effect as experimentally found, and somewhat more than this by computation. But the fact that this correction should be doubled when applied to the single (or real) zinc-bismuth effect was inadvertently overlooked.

Table II. shows that this correction (subtractive) for either single or double bobs on the long pendulums is 22 per cent., and, of course, grows rapidly as the pendulums are shortened.

It is seen that the very consistent results of single and double bobs of equal weight on the long pendulums indicate a zinc-bismuth effect of about one part in 32,000. But in all the pendulum and other experiments the end sought is not so much quantitative accuracy as qualitative certainty. In the present stage of the general investigation it matters little whether the true zinc-bismuth effect is one part in ten thousand or a hundred thousand; the great point is to make *sure* that it is *something* tangible. This is the purpose of my long course of experimentation.

Another, though small, correction might be made in Table II. (additive), due to the fact that the pendulum rods are of different material from the bobs.

Effect of Unequal Air Resistance.—I am often asked if performance of the pendulum experiments *in vacuum* might not greatly affect, or even obliterate, the apparent zinc-bismuth effect. To this I can confidently answer *no.* As I see it, the only thing to be gained by working in vacuum would be elimination of unequal air resistance due to the unequal diameters of the zinc and bismuth cylinders.

But this is easily compensated when working in air by attaching to the smaller bismuth cylinder small and very light vanes of paper or very thin aluminum normal to the line of swing of suitable area experimentally found or computed. This was always done in the foregoing experiments.

Careful experiments have shown that wholly uncompensated inequality of air resistance would increase the apparent zinc-bismuth effect only about 10 per cent. The effect of the air vanes on the bismuth is to slightly lengthen its period.

It is well known that wind pressure on a cylinder, normal to its axis, is approximately *half* that on a plane surface of a width equal to the diameter of the cylinder. Therefore, if we were to place on either double bob cylinder shown in Fig. 2 a plane air vane normal to line of swing, and as high and broad as a single cylinder, it would double the air resistance of that pair.

The diameters of the zinc and bismuth cylinders are, respectively, 72 and 61 mm., and their common height (single) 48 mm. Incidentally it will be seen that a zinc cylinder has 18 per cent. greater diameter than a bismuth cylinder, and presumably 18 per cent. more air resistance.

An air vane of thin cardboard 48 mm. high was placed on each double pendulum bob as shown in Fig. 2; that on the zinc 50 mm. wide, and on the bismuth 83 mm. wide, as shown by the dotted lines. The vanes were adapted to be turned into the line of swing, which

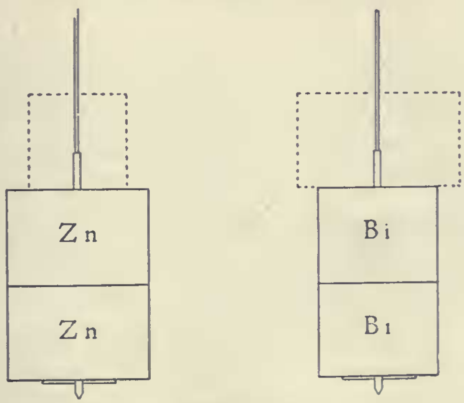

FIG. 2.

was equivalent to removing them, or normal to the swing, which would give them full effect.

It is easily seen that either vane, when turned normal to line of swing, *doubles* the air resistance of its pendulum as compared with the other pendulum having its vane in the line of swing.

Prior to adding these very large vanes, the pendulums had been synchronized and their bobs exchanged as in the last entry of Table II., showing the mean time required for the bismuth to gain one beat was 186 minutes.

When the air resistance of the zinc was thus made *double* that of the bismuth, the time required for the latter to gain one beat was 137 minutes. When these conditions were reversed, giving the bis-